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Virtual ballistic impact testing of Kevlar soft armor: Predictive and validated finite element modeling of the V_0-V_{100} probabilistic penetration response

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ABSTRACT

This works presents the first fully validated and predictive capability to model the V_0-V_{100} probabilistic penetration response of a woven fabric using a yarn-level fabric finite element model. The V_0-V_{100} curve describes the probability of complete fabric penetration as a function of projectile impact velocity. The exemplar case considered in this paper comprises of a single-layer, fully-clamped, plain-weave Kevlar fabric impacted at the center by a 17-gr, 0.22 cal FSP or fragment-simulating projectile. Each warp and fill yarn in the fabric is individually modeled using 3D finite elements and the virtual fabric microstructure is validated in detail against the experimental fabric microstructure. Material and testing sources of statistical variability including yarn strength and modulus, inter-yarn friction, precise projectile impact location, and projectile rotation are mapped into the finite element model. A series of impact simulations at varying projectile impact velocities is executed using LS-DYNA on the fabric models, with each model comprising unique mappings. The impact velocities together with the outcomes (penetration, non-penetration) are used to generate the numerical V_0-V_{100} curve which is then validated against the experimental V_0-V_{100} curve. The numerical V_i-V_r data (impact, residual velocities) is also validated against the experimental V_i-V_r data. For completeness, this paper also reports the experimental characterization data and its statistical analysis used for model input, viz. the Kevlar yarn tensile strengths, moduli, and inter-yarn friction, and the experimental ballistic test data used for model validation.

1. Introduction

Aramid (e.g. Kevlar, Twaron) woven fabrics are used in body armor systems for extremity protection and as backing for the ceramic torso plates. The penetration response of armor is probabilistic and represented by a V_0-V_{100} curve that describes the probability of complete fabric penetration (0–100%) as a function of projectile impact velocity (V). Sources of intrinsic and extrinsic statistical variability such as filament and yarn moduli and tensile strengths, inter-yarn friction, projectile impact location relative to the weave, and projectile trajectory contribute to the fabric probabilistic penetration response and the characteristic zone of mixed results (ZMR) that is observed during experimental testing [1]. The ZMR is the region between the lowest penetrating shot velocity (V_P) and highest non-penetrating shot velocity (V_{NP}) such that $V_P < V_{NP}$. Two metrics often used to assess and compare the performance of body armor systems are the back-face signature (BFS) and V_{50} velocity. The maximum allowable BFS, which determines if the armor provides sufficient protection against behind-armor blunt trauma (BABT) is 44 mm for 80% of all test shots at a 95% confidence level, and it should never exceed 50 mm [2]. The V_{50} velocity, which represents the projectile impact velocity that has a 50% probability of completely penetrating the armor target, can be estimated from a relatively few number of test shots (e.g. less than a dozen). However the V_{50} metric is not a very informative parameter. Instead, velocity performance metrics at the tail of the V_0-V_{100} curve, such as the V_1 or $V_{0.1}$ velocity, provide a better metric for armor applications, but require a large number of test shots to estimate with confidence. The precise probability level (e.g. 0.1%, 1%) used as the metric is determined based on acceptable risk.

For the past few decades, a slew of finite element studies have

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utilized fiber-level [3–7], yarn-level [8–16], and membrane-level [17–19] models to simulate the ballistic impact response of woven fabrics (primarily plain-weave Kevlar fabrics) as well as the transverse impact response of single yarns. In the fiber-level yarn and fabric models, individual fibers are discretized using 1D elements (e.g. trusses) and 3D elements (e.g. hexahedral solids). All the fibers within the yarn may be individually modeled (e.g. all 400 fibers of a 600 denier Kevlar KM2 yarn [6]) or only a subset of the fibers (19 of the 400 fibers [3]) depending on the intended resolution and computational requirements. In the yarn-level fabric models, individual warp and fill yarns are discretized using 1D elements (e.g. trusses), 2D elements (e.g. shells), and 3D elements (e.g. tetrahedral and hexahedral solids). In the membrane-level fabric models, the entire woven fabric ply is homogenized and discretized using 2D elements (e.g. membranes, shells). Typically, rate-insensitive orthotropic linear elastic material models are employed for the fibers and yarns of single-layer fabric models, however viscoelastic and elastic-plastic material models have also been utilized depending on available experimental data for model input. Yarn failure is typically modeled using element erosion based on a longitudinal tensile strength failure criterion, which is a reasonable assumption for single-layer fabric targets impacted by non-sharp projectiles at velocities between the V_1 and V_{99} velocities. However at very high velocities ($\gg V_{99}$) and for multi-layer fabric models, fiber and yarn transverse shearing and crushing failure modes need to be accounted for. Further details about these models are available in various review articles [20–23]. A decade ago, the high computational cost of yarn-level fabric models fully discretized with 3D finite elements limited the size of fabric targets modeled to a single ply of ~10 cm × 10 cm; however currently available high speed computing infrastructure enables the simulation of massive 3D yarn-level fabric finite element models (>300M degrees of freedom) that are representative of realistic-sized fabric ballistic test packs, such as 24 plies of 38 cm × 38 cm [1].

The entirety of the aforementioned finite element studies of fabric impact are deterministic and therefore incapable of generating a ZMR and a V_0-V_{100} curve. These deterministic models cannot shed light on how sources of material, geometry, and testing variability that are inherent in all composite fabric armor systems affect the probabilistic penetration response. Furthermore, some of these sources of stochastic variability are coupled with each other and interact differently depending on the impact scenario [24,25]. Thus, from the perspective of predictive virtual testing meant to reduce or replace dependence on experimental testing and from the perspective of practical armor design, such deterministic models of fabric impact are insufficient. The usefulness of these deterministic models is limited to studying qualitative deterministic trends while investigating the parametric effects of material, weave architecture, projectile characteristics, and target fixturing. The emphasis here is on general qualitative trends as opposed to precise quantitative predictions, therefore there is less scrutiny on model accuracy and the choices of input data and simplifying assumptions. Such insight is still useful in contributing to the overall understanding of the mechanisms of energy dissipation, deformation, and failure for various fabric target impact scenarios.

A much more challenging task lies in the quantitative validation of a deterministic model, that can accurately predict numerical results corresponding to performance metrics such as V_{50} velocity, residual projectile velocity, fabric dynamic deflection, and time required to arrest the projectile. For rigorous quantitative model validation, the choice of input data, assumptions, and methodologies becomes critical. In terms of quantitative deterministic predictions, two fabric impact studies in particular by Chocron et al. [26] and Wang et al. [3] have presented validation of their deterministic fabric models by comparing experimental V_{50} data with numerical deterministic V_{50} predictions, and then claimed the model predictions to be accurate. However, as discussed below, the reported validation does not appear to be consistent or rigorous and therefore cannot be considered an indicator of the predictive capability of these reported models; underscoring the exceedingly challenging nature of the problem of modeling predictive and quantitatively accurate fabric impact dynamics.

In the first example, Chocron et al. [26] used a yarn-level fabric finite element model to study the ballistic impact response of a multi-layer Kevlar fabric target, wherein each yarn was discretized with only two solid elements across the yarn width (i.e. diamond-shaped yarn cross-section) based on their previous findings with single-yarn transverse impact studies. However, those findings do not necessarily translate from a single-yarn model to a fabric model as the problem of single-yarn transverse impact essentially reduces to a 1D wave propagation problem that could be modeled and solved with any arbitrary yarn cross-sectional shape. In a woven fabric with interlacing yarns that interact with each other via frictional sliding and rotations, and load transfer mechanisms, the yarn cross-section needs be sufficiently discretized to capture the smooth elliptical or sinusoidal cross-sectional shape (e.g. Duan [27], Rao [10], Nilakantan [24]), which cannot be accomplished with only two elements across the yarn width. Chocron et al. [26] then reported scaling their fabric finite element model size to match the experimental fabric areal density. This step is deemed unnecessary with an appropriately modeled virtual fabric microstructure and consistently assigned homogenized yarn material densities as demonstrated later in Section 2.2.1. For their multi-ply fabric model, Chocron et al. [26] sourced the input material data from various experimental data published by other research groups [10,28]. Properties such as the yarn transverse compression modulus, transverse shear modulus, inter-yarn and inter-layer friction become important with multi-layer targets especially with the highly non-linear transverse compression behavior of multi-layer targets [29,30], through-thickness wave propagations, and the presence of multiple fiber and yarn failure modes such as transverse shear failure and fiber crushing. Whereas for single-layer woven fabric targets, a simple linear-elastic orthotropic set of yarn properties and a simple tensile failure criterion often suffices. Therefore, Chocron's selection of yarn properties from the literature [10,28] were not representative of the complexities of a multi-layer fabric target. Furthermore, the choice of yarn tensile strain to failure (and correspondingly yarn tensile strength) in Chocron's model that was sourced from the literature [10,28] did not account for the weaving strength degradations that are observed in the Kevlar fibers and yarns extracted from woven Kevlar fabrics, and also did not consider that the warp and fill fibers and yarns are degraded in strength to different extents [31,32]. Obviously the choice of yarn tensile strength is a critical determinant of the penetration response of the fabric during ballistic impact. Chocron's model did not address the issue of ply nestling and packing together observed in multi-layer fabric targets which is obviously not of concern in single-layer targets. Instead, Chocron's multi-layer fabric target was simply a replica of an individual ply copied multiple times and then stacked vertically with some small gap between each ply. The experimental ballistic testing conducted and reported by Chocron et al. [26] to validate their fabric finite element model acknowledged fabric slippage from the clamped edges. This is not a well set up experimental test to begin with, as boundary slippage is well known to significantly affect (incorrectly bias) the fabric ballistic impact response [33,34]. To remediate this, they used a fabric finite element model with free edges, however this already ensures an inconsistent comparison between experimental and simulation results because the impact event is wave